*Kufa Journal of Engineering*
*Vol. 7, No. 3, October 2016, P.P.66-79*
*Received on 20 March 2016, accepted on 28 May 2016*

# IMPROVEMENT OF LOOSE GRANULAR SOIL BY USING GEOGRID REINFORCEMENT

**Mohammed Kadum Fakhraldin[1]**

**[1] Dr. Lecturer, Civil Engineering Department, Faculty of engineering, university of Kufa, Al- Iraq, Al- Najaf , E-mail: kadum_fekheraldin@yahoo.com**

## ABSTRACT

There are several uses of granular soils in civil engineering works such as but not limited to under foundations structures, subbase course of roads, unpaved roads and soil embankments. This research attempts to overcome the problems of low-quality (by means of strength) of granular soil by enhancing **C**alifornia **B**earing **R**atio (CBR) test by utilizing geogrid. The research aim's to investigate the potential benefits of using the geogrid to improve CBR of granular soil. The results of tests showed that the granular soil under study was inferior than the materials comply on class C of Iraqi specifications for granular soil material. On the other hand, using of geogrid type Tensar SS2 at 0.15H (where H the total thickness of granular material samples) improves extremely the CBR value of the granular soil as it is increased by about three times in comparison with untreated soil.

**KEY WORDS:** Granular Materials, CBR, Soil Improvement, Geogrid

# تحسين التربةِ الحبيبيةِ الضعيفة بإستعمال تسليح المشبكات

**محمد كاظم فخرالدين**

**دكتور, مدرس, قسم الهندسة المدنية, كلية الهندسة, جامعة الكوفة, العراق – النجف**

**الخلاصة**

هناك عِدّة إستعمالات للتُرَبِ الحبيبيةِ في أعمالِ الهندسة المدنيةِ غير محدده تحت اسفل اسس المنشاءات فقط، لكن على سبيل المثال تستخدم في الطبقة الثانوية للطرقِ، طرق غير مُعَبّدة تعليات الترابيه. هذا البحثِ يُحاولُ التغلب على المشاكلَ واطئة التحمل (بواسطة القوّةِ) مِنْ التربةِ الحبيبيةِ بتَحسين نسبةِ اختبار تحمل كاليفورنيا (CBR) بإسْتِعْمال المشبكات, يهدف البحثَ لتَحرّي الفائدة المحتملةِ لإستعمال المشبكات لتَحسين نسبةِ تحمل كاليفورنيا في التربةِ الحبيبيةِ. بينت نَتائِجَ في الإختباراتِ بأنّ التربةَ الحبيبيةَ التي درست كانت اقل من صنف C حسب المواصفاتِ العراقيةِ لمادّةِ التربةِ الحبيبيةِ. من الناحية الأخرى، إستعمال مشبكات نوعِ Tensar SS2 على عمق H 0.15 (حيث H السُمك الكليّ للعيناتِ الماديةِ الحبيبيةِ في قالب CBR) تتحسن قيمةَ نسبةِ تحمل كاليفورنيا التربةِ الحبيبيةِ المسلحة بالمشبكات حوالي ثلاث مراتِ بالمقارنة بالتربةِ الغير مُعالجةِ.

## 1. INTRODUCTION

The amelioration of the stress-bearing capacity of the soil may be undertaken by variety of soil-improvement techniques. Many techniques are available to improve soil, such as compaction, preloading, drainage, grouting, chemical stabilization, electrical osmosis, stone columns, densification using vibratory equipment and using geosynthetics.

Earth reinforcement has been introduced into the field of soil engineering for many years in order to enhance the properties of the ground soil in specific technical projects. Conventional geosynthetics such as geofoam and geogrid have been proved to be efficient, and they are being increasingly used in soil engineering and other fields, (Long et al., 2007).

The definition of the granular soil differs among different soil classification systems, with limits being placed on soils with maximum fines percentages of 50% in accordance to ASTM (D2487, 2007). In addition, when the soils at site are loose or when they have unacceptable property that is making them unsuitable for use in a soil projects, they may have to be improved, (Bowles, J. E., 1996).

Reinforced geotechnical foundations may be used to construct superficial foundations on poor granular soils, soft fine-grained soils, or soft organic soils. Most reinforced soil foundations are constructed with the reinforcement placed horizontally; however, there are states in which vertical reinforcement perhaps be used. The reinforcement may consist of geogrid, geocell or other geosynthetics, (Geo-Institute Committee on Shallow Foundations, 2004).

Chen et al., (2014) investigated the shear behavior of mud stone coarse-grained soil reinforced with geogrid, the experimental investigations showed that geogrids considerably influence the shear behavior of mudstone coarse-grained soil, and geogrid reinforcement mainly improves the cohesive strength of coarse grained soil, thus improving its shear strength.

Qian et al., (2015) conducted shear resistance experiment on geogrid-reinforced railroad ballast samples using a big-scale triaxial test tool; they employee geogrids with triangular and square shape apertures to reinforce the two new and degraded (with and without fine particles littler than 9.5 mm) ballast samples. They founded the two triangular and square- opening geogrids to effectively increase the crest deviator pressure values for triaxial samples which were prepared using the new and degraded ballast materials, and the highest shear resistance values obtained for ballast samples reinforced using the square-opening geogrid.

Jawad and Baqir, (2009) studied the improvement of the engineering properties of soil mass by using bentonite. These properties included shear strength and maximum dry density. The experimental work showed that the ideal percentage of the bentonite can be taken as 7.5% to improve the properties of the soil as a material with good bearing capacity. They also concluded the increasing in the percent of bentonite from 2.5% to 7.5%, increase the cohesion (c) of soil a true amount and the bentonite increasing after 7.5% the increment of cohesion is became is very little.

Mohsen and Jawad, (2010) studied the effect of cement addition to the local granular materials used in roads and airports construction as a sub-base course on the results of CBR test and Atterberg limits and the aging time after which the specimen has been tested. The study showed that the ideal cement /granular materials ratio is 6% which more than 100% of the CBR value in comparison with the control samples. Also, the value of CBR increases to 170% after 7 days from the addition of water which contributed to the hydration of cement.

## 2. RESEARCH OBJECTIVES

There are sizeable areas of weak soil in Iraq, especially in the southern part, for construction due to poor strength and excessive settlement. However, replacing the loose soil and using piles, especially if the layer depth is more than two meters, are usually expensive and time consuming especially for small structures. Therefore, the soil improvement is the most suitable solution, (Al-Murshdi, 2001 and Dalaly et al., 2015).

The main objective of this study is to inspect the possibility of reinforcement of granular soil having a low-CBR value with geogrid. The granular soils were stabilized by placing geogrid at various depths, resulting in a granular soil-reinforcement that is suitable for soil under shallow foundation and a road base or road sub-base layer. Also, the research investigated only one granular soil type and one type of geogrid. Hence, the only variable remaining was the value of the best suitable depth under foundation which is nominated as u within this study. The modified compaction test was employed to find the maximum dry unit weight as well as optimum water content (OWC). Then, this OWC values were used to prepare specimens for the California Bearing Ratio (CBR) test both soaked and unsoaked. Note that the CBR values are the main property that is required for the design of embankments and road.

## 3. MATERIALS AND TEST PROGRAMS

### 3.1. MATERIALS

#### 3.1.1. Granularsoil

About 1.5 $m^3$ of Al-Najaf granular soil were prepared in the laboratory. Sieve analysis for the granular soil was carried out and the grain size distribution curve was obtained as shown in Fig. 1.

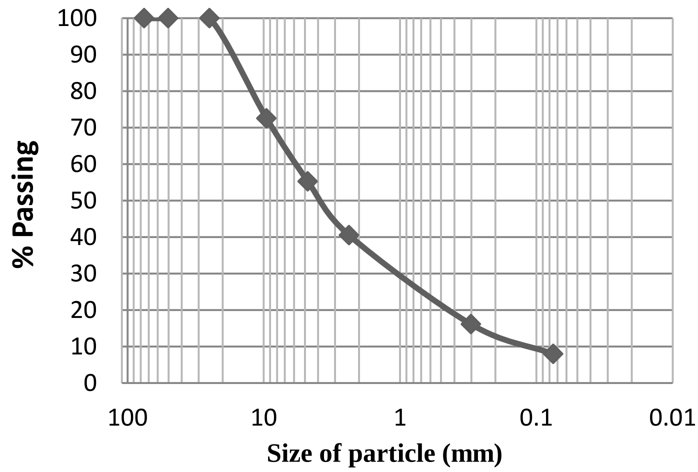



**Fig. 1. Particle size distribution of the granular soil**

The chemical and physical properties are summarized in Table 1.

**Table 1. Physical and chemical properties of the granular soil**

| The Chemical Properties | |
|---|---|
| $SO_3$ | 3.6% |
| T.D.S | 0.75% |
| Gypsum content | 7.76% |
| **The physical properties** | |
| $G_s$ | 2.7 |
| Organic Content | 3.88% |
| O.M.C | 12.85% |
| $\gamma_{dry\ max}$ (MDD) | 19.2 kN/m$^3$ |
| $D_{60}$ | 0.4mm |
| $D_{50}$ | 0.365mm |
| $D_{30}$ | 0.28mm |
| $D_{10}$ | 0.185mm |
| $C_u$ | 2.16 |
| $C_c$ | 1.06 |
| w.c | 2.5% |

The tests are performed on granular soil with maximum dry density of the granular soil decided depending to the ASTM specifications, (D1557, 2007). The specific gravity test is carry out according to ASTM, (D854-05, 2007) and the particle size distribution is performed according to ASTM, (D422-63, 2007). The chemical tests of the granular soil were performed according to the British Standard, (BS 812, 1988).

The granular soil is classified as Class C according to Iraqi specifications for granular soil material, (R6 02 materials, 2007)

### 3.1.2. Geogrid (Tensar SS2)

Geogrids are matrix such as materials with big open spaces called apertures, which are typically 1 to10 cm between Costas that are called longitudinal and transvers**,** respectively. The Costas themselves can be manufactured from a number of different materials, and the rib cross-over joining or junction- tying methods can vary. The initial function of geogrids is clearly reinforcement, (Koerner, R.M., 2005).

According to ASTM geogrid, a geosynthetic shaped by a regular mesh of integrally joined elements with apertures greater than 0.635 cm (1⁄48 ft) to allow interlocking with banding materials to primarily employment as reinforcement. Ribs for geogrids are the continual elements of a geogrid, which are either in the instrument or cross- instrument direction as manufactured. Junction is the dot where geogrid ribs are interconnected to provide structure and dimensional stability, (D6637-01, 2007).

Geogrid tests are unique in a number of aspects when compared with geotextiles. The properties that relating to separation, filtration, drainage, and barrier applications are not included, since geogrids always serve the primary function of reinforcement, (Koerner, R.M., 2005).

Tensar SS2 was manufactured by the British Company Netlon ltd. The physical and mechanical properties of this type of geogrid are summarized in the Table 2, (Fakharaldin, M.K., 2013).

**Table 2. Physical and mechanical properties of Tensar SS2 geogrids, after Fakhraldin.**

| The physical properties | | |
|---|---|---|
| Property | | Data |
| Mesh type | | square |
| Standard color | | Black |
| Polymer type | | PP |
| Packaging | | Rolls |
| **Dimensional Properties** | | |
| Property | Unit | Data |
| Aperture size(MD/XMD) | mm | 28/40 |
| Mass per unit area | $kg/m^2$ | 0.3 |
| Rib thickness MD/XMD | mm | 1.2/1.1 |
| Junction thickness | mm | 3.9 |
| Longitudinal rib width lw | mm | 3 |
| Transverse rib width tw | mm | 3 |
| Roll width | m | 4 |
| Roll length | m | 50 |
| **The Mechanical Properties** | | |
| Peak Tensile Strength MD/XMD | kN/m | 14.4/28.2 |
| Elastic modules MD/XMD | GPa | 0.57/0.99 |
| Upper yield strength MD/XMD | MPa | 1 /3 |
| Lower yield strength MD/XMD | MPa | 1/3 |
| Tensile strength MD/XMD | MPa | 24/30.7 |

## 3.2. TEST PROGRAMS

The experimental work consists of laboratory model tests to investigate the improvement in bearing capacity and reduction in settlement of granular soil by using geogrids reinforcement.

Two main categories were conducted in the experimental work; the first was conducted to find the physical and chemical properties for the granular soil, while the second included the evaluation of the potential shear strength for granular soil by using CBR test with and without geogrid.

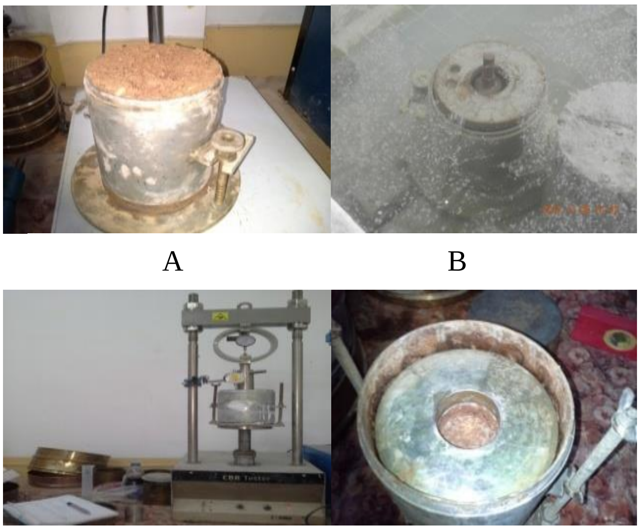
CBR testing was carried out in accordance to ASTM, (D1883, 2007) with and without geogrid layers. The CBR test dependent primarily on the values of OMC and MDD which are obtained from compaction test. The CBR test required three samples for each test, the first was compacted by 10 blows, while the second and third were compacted by 30 and 65 blows for each layers, respectively.

The samples of CBR were prepared according to (D1883, 2007); the samples were compacted in CBR mold according to D4253 and with OMC given from compaction test in three layers. CBR value has been considered for the 95% of the maximum dry density for CBR values with and without geogrid. CBR values of samples without geogrid have been considered as references for comparison to study the benefit of adding the geogrid. Four geogrid positions which were used i.e. 0.1, 0.15, 0.2 and 0.25 from the height of the specimens.

## 4. THE STEPS OF TESTS

### 4.1. WITHOUT GEOGRID

Three samples of CBR mold were prepared for test, all samples were prepared with OMC which is 12.85% and compacted in three layers i.e. 10, 30 and 65 blows for each mold respectively, then all samples were soaking in water for 4 days, after performed CBR test. The steps of preparation the samples of CBR mold and test are shown in Fig. 3 (A-D). The results obtained from CBR tests were computed (displacement and pressure) and the drawing between displacement and pressure has been done to indicate the CBR values for each samples at 1 in (2.5 mm), finally a sketch were drawn between CBR values and dry density to find values of CBR which to meet dry field density (0.95 from maximum dry density).




C D

**Fig. 2. Processor of CBR preparation and test**

### 4.2. WITH GEOGRID

Geogrid layers were placed perpendicular to applied or vertical load in other word the layer acts horizontally in the mold of CBR and four position of geogrid were investigated to predict the best position of the first layer from foundation (u). The depth of geogrid layers were presenting as ratio from height (H) of specimens as 0.1, 0.15, 0.2 and 0.25 from the height of the specimens (H), as shown in Fig. 4 (A-E).

The aperture size of the meshes was considered to be reasonable in reference to the scale of the CBR specimens (mold diameter 6 in or 150 mm), (Al-Omari, R. R., et al., 1989). In this study two layers of geogrid of Tensar SS2 (2 * SS2) were stitched together to form a single layer of reinforcement with opposite aperture to reduce the aperture size of geogrid (28*40 mm) to half size (14*20 mm) and obtained double stiffness. The aperture size of the geogrid was 14 mm by 20 mm, which is appropriate to the size of the granular soil particles, (Al-Omari, R. R., et al., 1987).

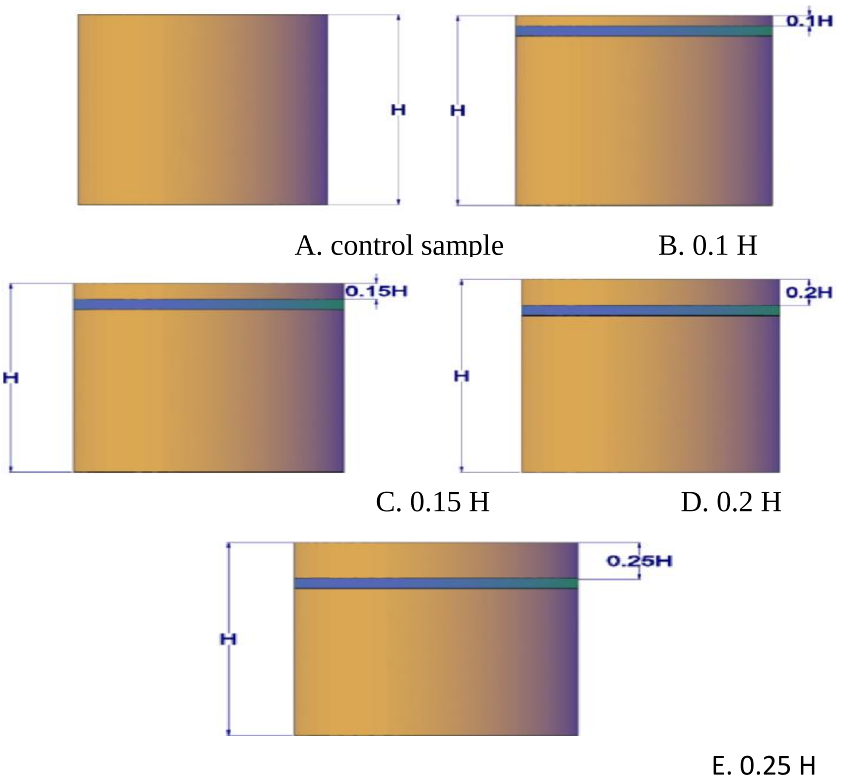



**Fig. 3. CBR testing samples with and without reinforcement**

## 5. CBR RELATED TO THE BEARING CAPACITY

The CBR test is essentially tests which result in shear failure of the soil under the plunger. Shear failure occurs when the ultimate bearing capacity is reached. The ultimate bearing capacity of the soil under the circular plunger can be determined by Terzaghis method. It may be assumed that at a penetration of 0.1 in (2.5mm). The stress applied to the soil is close to its ultimate bearing capacity named $P_f$. The ultimate bearing capacity of the soil under the circular plunger can be determined by Terzaghi's method. The stress on the standard material at 0.1in penetration is 1000 psi yielding as follows in equations (1), (2) and (3), (Terzaghi et al., 1996).

$$CBR = (P_{0.1}/P\ soil)*100 = (P_f/1000)*100 \quad (1)$$

$$CBR=P_f/10 \quad (2)$$

So

$$P_f\ (psi) = 10*CBR \quad (3)$$

## 6. THE EXPERIMENTAL RESULTS AND DISCUSSION

The values of CBR are depend mainly on the field dry density, the field density was considered as 0.95 from maximum dry density, therefor the CBR values for all the case studies which are needed to indicate the CBR value with 0.95 of the maximum dry density in accordance to ASTM, (D1883, 2007), test method and these values were used for comparison studies.

Figure (4) below indicates the relation between CBR and dry unit weight, the CBR and dry unit weight in Fig. 4 obtained from three attempts, the first sample subjected to 10 blows of each layers, the second sample subjected to 30 blows and the third sample subjected to 65 blows, the value of CBR against 95% maximum dry unit weight for granular soil without geogrid is nine, this value is considered reference value to investigated the amount of improvement of CBR after using geogrid and named CBR of unreinforced granular soil and denoted as $CBR_u$.

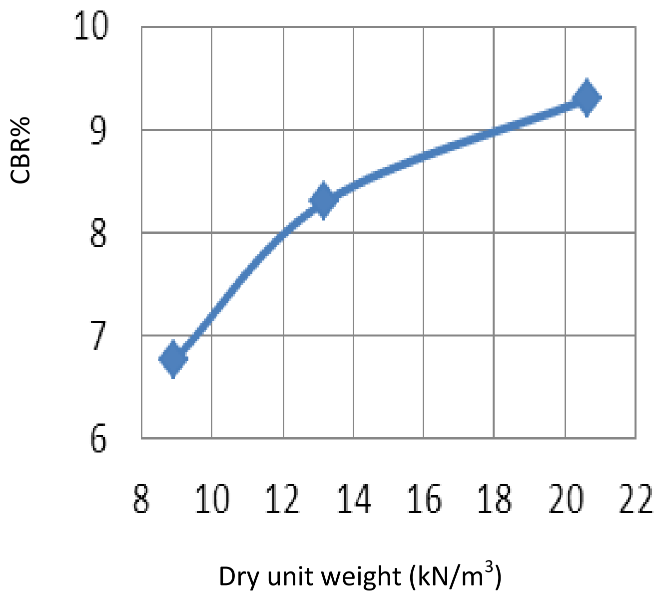



**Fig. 4. Relation between CBR and dry unit weight without geogrid**

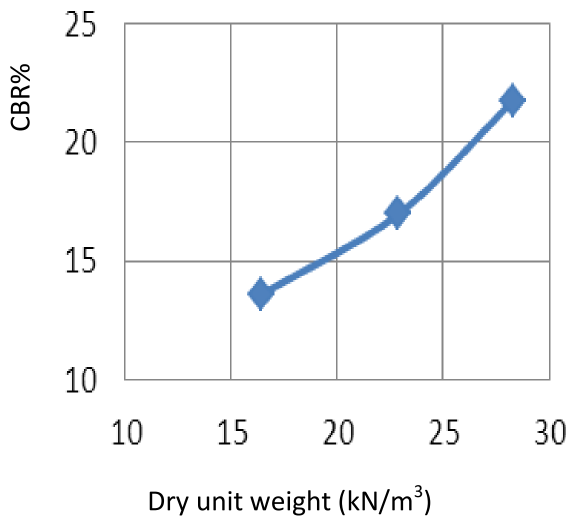



**Fig. 5. Relation between CBR and dry unit weight with geogrid at 0.1H from base**

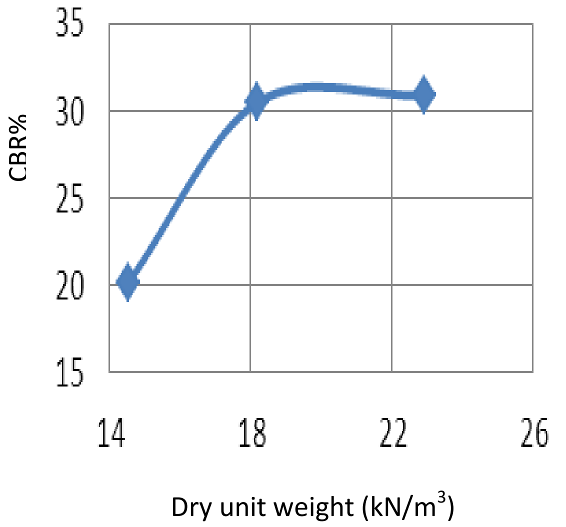



**Fig. 6. Relation between CBR and dry unit weight with geogrid at 0.15H from**

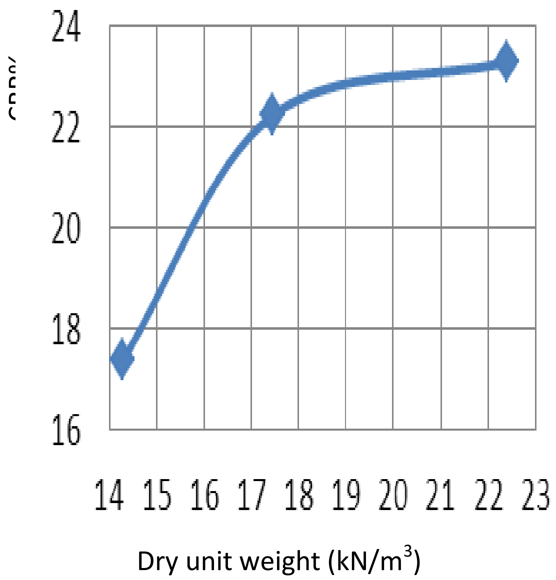



**Fig. 7. Relation between CBR and dry unit weight with geogrid at 0.2H from**

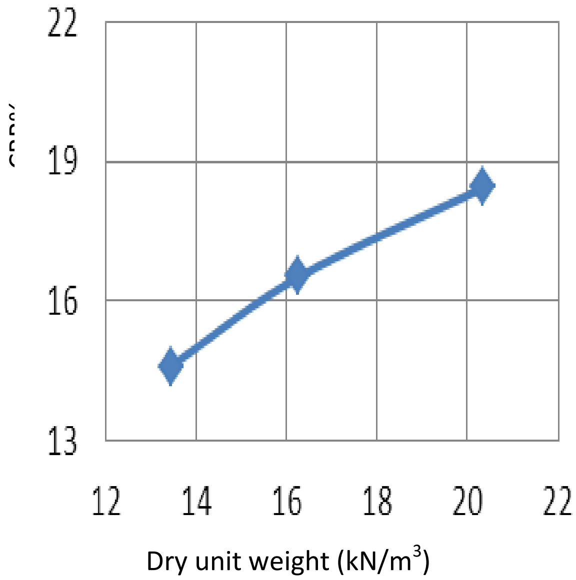



**Fig. 8. Relation between CBR and dry unit weight with geogrid at 0.25H from**

Figs. 5-8 below shows the relation between CBR and dry density for 0.1H, 0.15H, 0.2H and 0.25H depth of geogrid layer from base to find the best position of the first layer of geogrid from the top of the mold (u), the values of CBR which meet the values of 0.95 from maximum dry density, named CBR of reinforced granular soil and denoted as $CBR_r$, the values of $CBR_r$ are increased slightly compared with $CBR_u$, the trend in figures blow is difrent because the difrent position of geogrid in the granular soil.

The values of $CBR_r$ are increased slightly compared with $CBR_u$, the values of $CBR_u$ and $CBR_r$ are scheduled in the Table 3 below and presented the degree of improvement (degree of improvement is the ratio between $CBR_r$ / $CBR_u$).

**Table 3. Values of $CBR_u$ and $CBR_r$**

| Depth of geogrid (u) | CBR % | $CBR_r/CBR_u$ |
|---|---|---|
| Without geogrid | 9 | |
| 0.1 H | 14.5 | 1.611 |
| 0.15 H | 30.6 | 3. 4 |
| 0.2 H | 22.6 | 2.51 |
| 0.25 H | 17.3 | 1.922 |

The results in the table 3 are sketched in Figs. 9 and 10 between CBR at 0.95 of maximum dry density for reinforced cases and position of geogrid (u), the observation of the results in table 3 and Figs. 9 and 10 we find the values of CBR and degree of improvement are gradually increasing until reached the ratio (0.15H) then its decreases gradually, the best position of the geogrid (u) at the crest of curve when depth equal 0.15 H from the surface andobtained the highest value of CBR and degree of improvement are 30.6 and 3.4 respectively.

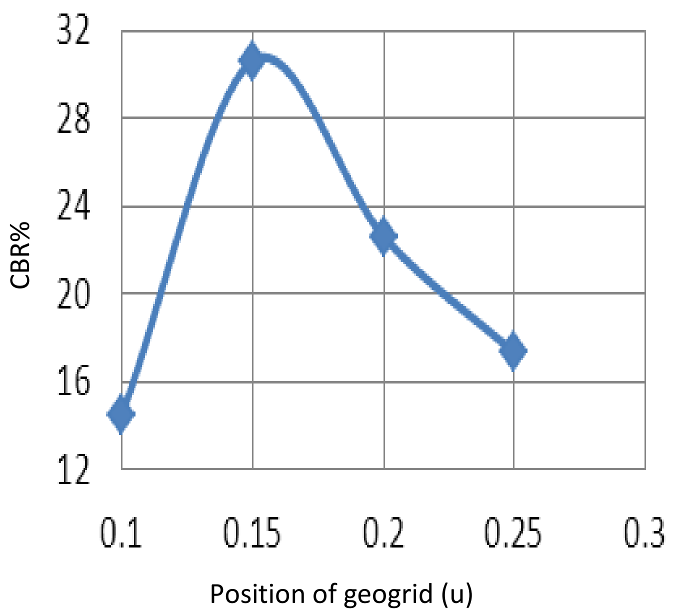



**Fig. 9. Relation between various positions of geogrid**

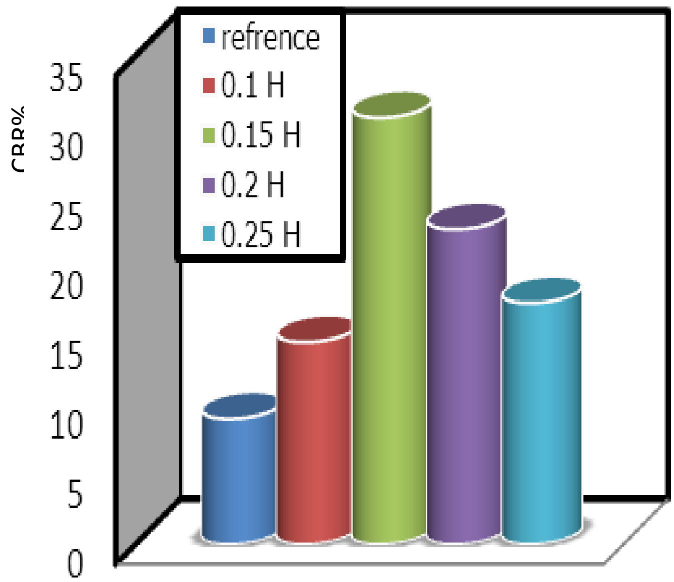



**Fig. 10. CBR for different cases models**

Fig. 11 shows the values of CBR and dry unit weight were drawn of different design models with and without geogrid and including the numbers of blows of each layers are 10, 30 and 65 blows, when observation the curves in Fig. 11, it is found that the dry density also increased when using geogrid in granular soil, in the other words when using geogrid in the granular soil are enhancement the physical properties such as dry density as shown the results in Table 4 below.

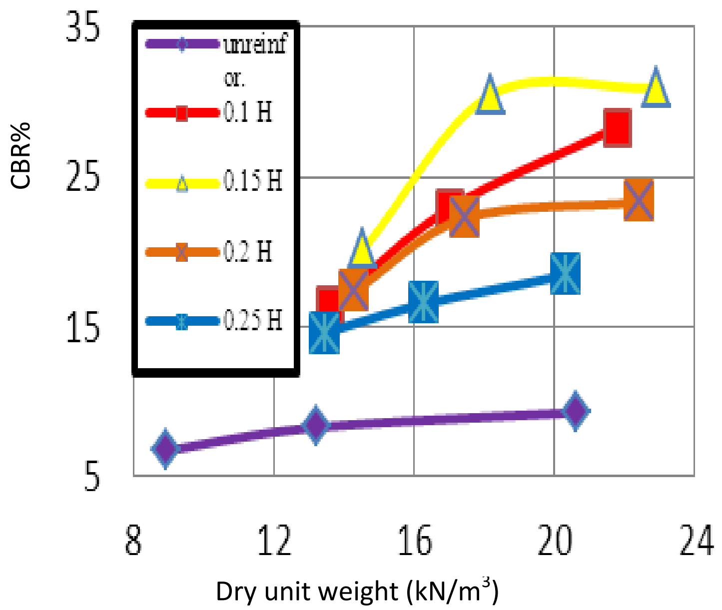



**Fig. 11. Relation between CBR and dry unit weight with and without geogrid for various cases**

**Table 4. Degree of improvement of dry unit weight**

| Model of Sample | No. of blows | (γdry)r/ (γdry)u |
|---|---|---|
| 0.1 H | 10 | 1.53 |
| | 30 | 1.29 |
| | 65 | 1.06 |
| 0.15 H | 10 | 1.63 |
| | 30 | 1.38 |
| | 65 | 1.11 |
| 0.2 H | 10 | 1.61 |
| | 30 | 1.32 |
| | 65 | 1.09 |
| 0.25 H | 10 | 1.51 |
| | 30 | 1.23 |
| | 65 | 1.01 |

The extremely improvement of the shear strength (CBR) and dry unit weight of the soil reinforcement were attributed to that the employment of geogrid is based upon the emergence of tensile tie on the soil with geogrid interface which bind the motion of soil particles and this tie is due to friction, adhesion and interlocking, (Al-Omari, R. R. and Hamodi, F. J., 1991). It is technique of reinforced granular is very important and useful for foundation, airfield and unpaved road, for foundation it is increasing bearing capacity of soil under foundation to reduce the expansive cost of constructed deep foundation also for airfield it used to strengthen the subbase to resistance impact load and for unpaved road it is very important to reduce settlement and amount of materials of layers on the other words for special case of road may use this technique when cannot use paved road.

## 7. CONCLUSIONS

Preliminary, the present investigation is concerned with studying the physical and mechanical peculiarities of granular materials and geogrid materials. The main experimental program involved shear strength tests representing by CBR test using five models; they are one CBR model alone and four models type of CBR with reinforcement using geogrid type Tensar SS2 with different depths from base of model are 0.1, 0.15, 0.2 and 0.25from thickness from the height of the granular soil layer.

Based on the experimental study, the following conclusions may be drawn:

a. The values of CBR are increased when geogrid is inserted in the granular soil at different depths from thickness from height of the granular soil layer.
b. The best depth of the first layer (u) of geogrid in granular soil using Tensar SS2 was found at depth 0.15 from thickness from height of the granular soil layer.
c. CBR value for the crest point increased more than three times when compared with unreinforced soil.
d. The dry density of the granular soil increases when using geogrid in the CBR models.
e. The optimum values of dry density increased more than one – half times compared with untreated soil.
f. The largest dry density was obtained from model of geogrid depth 0.15 from thickness from height of the granular soil layer and 10 blows mold.

## 8. ACKNOWLEDGMENTS

Special thanks are presented to Dr. ABBAS AL-HDABI and Mr. Mohammed Hammed and deepest wishes to my students Miss. Sundus Ali Shukur and Miss. Meryam Mansoor.

## 9. REFERENCES

Al - Murshdi, M. A., (2001), “Effect of Granular Trench in Soft Clay on Bearing Capacity of A Strip Foundation”, Ms.c thesis, University of Al-Mustansiriya, Iraq.

A l- Omari, R. R., Al-Dobaissi, H. H. and Al-Wadood, B. A., (1987), “Inextensible Geomesh Included in Sand and Clay”, Prediction and Performance in Geotechnical Engineering/Calgary/17-19 June, pp. 155-160.

Al - Omari, R. R., Al-Dobaissi, H. H. and Al-Wadood, B. A., (1989), “Shear Strength of Geomesh Reinforced Clay”, Journal of Geotextiles and Geomembranes, No. 8, pp. 325-336.

Al - Omari, R. R. and Hamodi, F. J., (1991), “Swelling Resistant Geogrid-A New Approach for the Treatment of Expansive Soils”, Journal of Geotextiles and Geomembranes, No. 10, pp. 295-317.

ASTM D422-63, 2007, “Standard Test Method for Particle Size-Analysis of Soils”, American Society for Testing and Materials.

ASTM D854-05, 2007, “Standard Test Method for Specific Gravity of Soil Solids by Water Pycnometer”, American Society for Testing and Materials.

ASTM D1557, 2007, “Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort”, American Society for Testing and Materials.

ASTM D 1883, 2007, “Standard Test Methods for CBR California Bearing Ratio”, American Society for Testing and Materials.

ASTM D2487, (2007), “Unified Soil Classification System”, American Society for Testing and Materials.

ASTM D6637-01, 2007, “Standard Test Method for Determining Tensile Properties of Geogrids by the Single or Multi-Rib Tensile Method”, American Society for Testing and Materials.

Bowles, J. E., 1996, “Foundation Analysis and Design”, 5th Edition, McGraw-Hill Book Company, Inc, USA.

BS 812, (1988) and ICS 91.100.15 71.080.01 19.020, manual 895/2003, “Testing Aggregates”, Part 118, Method for Determination of Sulphate Content.

Chen, X., Zhang, J., and Li, Z., (2014), “Shear Behaviour of a Geogrid-Reinforced Coarse-Grained Soil Based on Large-Scale Triaxial Tests”, Journal of Geotextiles and Geomembranes, No. 42, pp. 312-328.

Dalaly N. K., Al-Soud M. S. and Abdul Jabar S. S., (2015),”New Technique of Strengthening Soft Soil under a Strip Footing by a Granular Trench Reinforced with Geogrid Micro Mesh”, Australian Journal of Civil Engineering, Vol. 13, Issue 1, PP. 11-21.

Fakharaldin, M.K., (2013),”Properties Measurement and Applications of Some Geogrid in Sand”, Ph.D. Thesis, Alnahrain University, Iraq.

General Specifications for roads and bridges in Iraq, 2007.

Geo-Institute Committee on Shallow Foundations, (2004), “Bearing Capacity and Settlement of Shallow Foundations on Reinforced Soil”, A Bibliography of the Technical Literature.

Jawad T. A. and Baqir A. M., (2009),” Studing the Improvement of Soil Properties by Using Bentonite”, Kufa Journal of Engineering, Vol. 1, No.1, pp.29-39.

Karl Terzaghi, Ralph B. Peck and Gholamreza Mersi, (1996), “Soil Mechanics in Engineering Practice”, Third Edition, John Wiely and Sons. Inc. New York

Koerner, R.M., (2005), “Design with Geosynthetics”, 5th Edition, Library of Congress Cataloging, Publisher’s.

Long, P. V., Bergado, D. T., Abuel-Naga, H. M., (2007), “Geosynthetics Reinforcement Application for Tsunami Reconstruction: Evaluation of Interface Parameters with Silty Sand and Weathered Clay”, Journal of Geotextiles and Geomembranes, No. 25, pp. 311-323.

Mohsen A. T. and Jawad T. A., (2010)," Influence of Cement as Additive in Improving Granular Material Properties", Kufa Journal of Engineering, Vol. 1, No.2, pp.175-184.

Qian, Y., Mishra, D., Tutumluer, E. and Kazmee, H. A., (2015), "Characterization of Geogrid Reinforced Ballast Behavior at Different Levels of Degradation Through Triaxial Shear Strength Test and Discrete Element Modeling", Journal of Geotextiles and Geomembranes, No. 43, pp. 393-402.